On a possible photon origin of the most-energetic AGASA events

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In this work the ultra high energy cosmic ray events recorded by the AGASA experiment are analysed. With detailed simulations of the extensive air showers initiated by photons, the probabilities are determined of the photonic origin of the 6 AGASA events for which the muon densities were measured and the reconstructed energies exceeded 10^{20} eV. On this basis a new, preliminary upper limit on the photon fraction in cosmic rays above 10^{20} eV is derived and compared to the predictions of exemplary top-down cosmic-ray origin models.

1. Photons as UHECR?

Studies on ultra-high energy photons as primary cosmic rays have the potential to discern between different models of origin of ultra-high energy cosmic rays (UHECR). Many top-down scenarios predict a dominance of photons in the CR flux above 10^{20} eV (for a review see [1]), while according to classical acceleration scenarios in this energy range the CR flux should consist mainly of hadrons. Thus, any experimental conclusions about a fraction of photons in UHECR, e.g. an upper limit on this fraction, are expected to provide constraints for the models of UHECR origin.

Presently, there are few experimental upper limits on photon fraction estimated on the basis of cosmic rays of energies above 10^{19} eV ([2], [3]). They are plotted in Fig. 1 and compared to the predictions of the three exemplary top-down models: super heavy dark matter (SHDM) [4], Z-bursts (ZB) and topological defects (TD) [5]. It can be seen that the available limits are not very constraining since below 5×10^{19} eV a typical predicted photon fraction is still low. Above 10^{20} eV, where the photon fraction predictions are larger, there is no experimental upper limit, although there are a few well documented cosmic ray events of such extremely large energies. While large amount of UHECR data from next generation giant cosmic-ray detectors is still on their way, in this work the available data of extensive air showers detected by the AGASA experiment are analysed to derive an upper limit on the photon fraction in UHECR. In order to determine the probability of an event being initiated by a photon the muon densities measured on ground, which are expected to be good indicators of primary mass [6,7], were compared to the simulations.

2. AGASA cosmic ray data above 10^{20} eV

Among the 11 cosmic ray events above 10^{20} eV recorded by the AGASA experiment [8,2] in 6 cases the muon densities at a distance of 1000 m from the shower core ($\rho_\mu(1000)$) were measured and published in Ref. [2] (see Table 1). The accuracy of $\rho_\mu(1000)$ was evaluated to be $\sim 40\%$ [2].

2.1. Simulations

The published energies and arrival directions were used for the simulation of photon-induced air showers. The effect of pre-cascading of photons in the geomagnetic field (preshower effect) [9, 10] and the subsequent air shower simulations were performed with use of the CORSIKA package [11] with coupled PRESHOWER code [12]. For each of the 6 events with available experimental $\rho_\mu(1000)$ values, 100 photon-induced showers were simulated. This allowed obtaining 6 distributions of simulated muon densities $\rho_{\mu,sim}(1000)$ at the observational level.

The exact values of the reconstructed primary energies E_0 were published in Ref. [13] and updated on the AGASA web page [14]. These values were obtained with accuracy of 25%, assuming that all the showers were initiated by hadrons. As noted in Ref. [2], for photon-induced showers, E_0 underestimates the real primary energy by about 20%. This 20% correction was applied in all the photon-induced shower simulations presented here.

2.2. Probabilities of photonic origin

The basic approach to determine the probability of a primary photon origin of an individual event is quite similar to the one outlined in Ref. [15]. The simulated distributions of $\rho_{\mu,sim}(1000)$ were compared to the experimental values in the following way. It is assumed that the uncertainties connected to the measurements of the muon density $\rho_\mu(1000)$ for each AGASA event follow the Gaussian distribution with the uncertainty $\sigma_{\rho_\mu(1000)} = 0.4\rho_\mu(1000)$. The simulations for the energy and arrival direction of the j-th recorded event gave $n = 100$ expected values $\rho^{ij}_{\mu,sim}(1000)$, where index i denotes the i-th simulated shower. The probability P^{ij} that $\rho^j_\mu(1000)$ differs by more than δ^{ij} from the expected muon density $\rho^{ij}_{\mu,sim}(1000)$ is given by

$$P^{ij} \equiv P(|\rho^{ij}_{\mu,sim}(1000) - \rho^j_\mu(1000)| > \delta^{ij}) = \\ = 1 - \int_{\rho^j_\mu(1000)-\delta^{ij}}^{\rho^j_\mu(1000)+\delta^{ij}} f(x, \rho^j_\mu(1000))dx, \quad (1)$$

with $f(x, \rho^j_\mu(1000))$ being the Gaussian distribution. Since $\sigma_{\rho_\mu} \approx 0.4\rho_\mu$, f has a small (less than 1% of $\int f(x)dx$) contribution from negative values of muon densities x. This contribution was accounted for by a simple renormalization of P^{ij}. The probability for the j-th event being initiated by an UHE photon, P^j_γ, was obtained by taking the average P^{ij} values. The experimental data together with the results of the simulations and analysis are collected in Table 1. For each event, the probabilities P^j_γ are small, but not negligible.

3. Upper limit on photon fraction in UHECR above 10^{20} EeV

After the probabilities P^j_γ have been determined, the upper limit for the photon fraction in the cosmic rays with $E_0 > 100$ EeV can be estimated in the following way. Let us calculate the probability that N_γ out of 6 AGASA events were induced by photons:

$$P(N_\gamma = n) = \sum \prod_{k=1}^{n} P^{j_k}_\gamma \prod_{l=1}^{6-n} (1 - P^{i_l}_\gamma) \quad (2)$$

where $j_k, i_l \in \mathbf{A} = \{1, ..., 6\}$, $\forall\ k, l \in \mathbf{A} : j_k \neq j_l$ and the summation extends over all n-elemental combinations of indices j_k in $\mathbf{A}$. The values of $P(N_\gamma = n)$ are collected in Table 2. These values determine the upper limit on gamma fraction in cosmic rays. The probability that less than 3 out of the analysed 6 AGASA events with $E_0 > 100$ EeV were initiated by photons is larger than 95%, i.e. $P(N_\gamma/N < 3/6) > 95\%$. This allows the conclusion that the upper limit on the photon fraction in cosmic rays above 10^{20} eV equals $3/6 = 50\%$ at 95% confidence level.

Table 1
Average muon densities $\langle\rho^{ij}_{\mu,sim}(1000)\rangle$ and their RMS fluctuations simulated at ground level for the AGASA events with $E_0 > 10^{20}$ eV are compared to the experimental values $\rho^j_\mu(1000)$. The E_0 values are increased by 20% with respect to the published data. The probabilities P^j_γ that the j-th event was initiated by an UHE photon are given. The azimuths of the arrival directions increase clockwise from North. For the analysis method see the text.

AGASA data						
E_0 [EeV]	295	240	173	161	126	125
zenith [°]	37	23	14	35	33	37
azimuth [°]	260	236	211	55	108	279
$\rho^j_\mu(1000)$ [m^{-2}]	8.9	10.7	8.7	5.9	12.6	9.3
simulations						
preshowers [%]	100	100	96	100	93	100
$\rho^{j,s}_\mu(1000)$ [m^{-2}]	4.3	3.1	2.1	2.3	1.7	1.8
RMS($\rho^{j,s}_\mu$)[m^{-2}]	0.7	0.6	0.8	0.3	0.4	0.3
P^j_γ [%]	19.5	7.3	6.0	12.3	2.4	3.8

Table 2
Probability that N_γ out of the 6 AGASA events were initiated by a photon.

N_γ	0	1	2	3	4	5	6
P[%]	57.8	34.0	7.4	0.8	4E-2	1E-3	1E-5

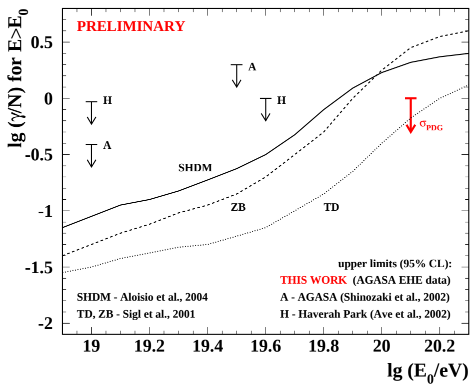

Figure 1. The ratio of photon-induced showers to hadron-induced ones as a function of the primary particle energy [2]. The upper limits obtained by the AGASA and Haverah Park experiments at 95% CL are indicated by arrows. For explanation of the theoretical models see the text.

4. Discussion

The obtained 50% upper limit on gamma fraction corresponds to $N_\gamma/N_{nucl}(> 10^{20}\text{eV}) < 1$. In Fig. 1, the above result is compared to the theoretical expectations of exemplary top-down models of cosmic ray origin and to the previous experimental upper limits on the photon fraction in UHECR of energies above 10^{20} eV. The models that predict gamma fractions higher than the obtained upper limit are disfavored by the AGASA data.

It should be noted that a considerable systematic uncertainty is related to extrapolating the photonuclear cross-section $\sigma_{\gamma-air}$ to highest energies [16]. In relation with the current analysis, assuming that $\sigma_{\gamma-air}$ increases more rapidly at highest energies would result in larger muon densities on ground and hence in larger probabilities of photonic origin of the analysed events. This will be discussed elsewhere.

The presented analysis method of determining the upper limit of photon fraction can be used as well for a larger data sample which is expected soon from the new generation cosmic ray detectors. The conclusions based on these new data should offer a good way to distinguish between different models of cosmic ray origin.

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REFERENCES

1. P. Bhattacharjee and G. Sigl, *Phys. Rep.* **327** (2000) 109
2. K. Shinozaki et al., *Astrophys. J.* **571** (2002) L117; K. Shinozaki et al., Proc. 28th Int. Cosmic Ray Conf., Tsukuba, **1** (2003) 401
3. M. Ave et al., *Phys. Rev. Lett.* **85** (2000) 2244; M. Ave et al., *Phys. Rev. D* **65** (2002) 063007
4. R. Aloisio et al., *Phys. Rev. D* **69** (2004) 094023
5. G. Sigl, hep-ph/0109202 (2001)
6. X. Bertou et al., *Astropart. Phys.* **14** (2000) 121
7. A.V. Plyasheshnikov and F.A. Aharonian, *J. Phys. G* **238** (2002) 267
8. H. Ohoka et al., *Nucl. Instr. Meth.* **A385** (1997) 268
9. T. Erber, *Rev. Mod. Phys.* **38** (1966) 626
10. B. McBreen and C. J. Lambert, *Phys. Rev. D* **24**, (1981) 2536
11. D. Heck et al., Report **FZKA 6019**, Forschungszentrum Karlsruhe (1998); D. Heck and J. Knapp, Report **FZKA 6097**, Forschungszentrum Karlsruhe (1998)
12. P. Homola et al., astro-ph/0311442 (2003); P. Homola et al., this volume
13. M. Takeda et al., *Phys. Rev. Lett.* **81** (1998) 1163; N. Hayashida et al., astro-ph/0008102 (2000)
14. AGASA official web page: http://www-akeno.icrr.u-tokyo.ac.jp/AGASA/pub
15. M. Risse et al., *Astropart. Phys.* **21** (2004) 479
16. M. Risse et al., this volume, astro-ph/0410739 (2004)